PASSIVE AND ACTIVE CONTROL FOR REHABILITATION ROBOTS

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Outline

- Background
- Review of Rehab Robotics Research
- Research on Upper-limb Rehab Robot
- Research on Lower-limb Rehab Robot

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- Background
  - Neurological Injuries: Stroke and SCI (Spinal Cord Injury)
  - Motor Plasticity and Rehabilitation
  - Manual Training VS Robot-aided Training
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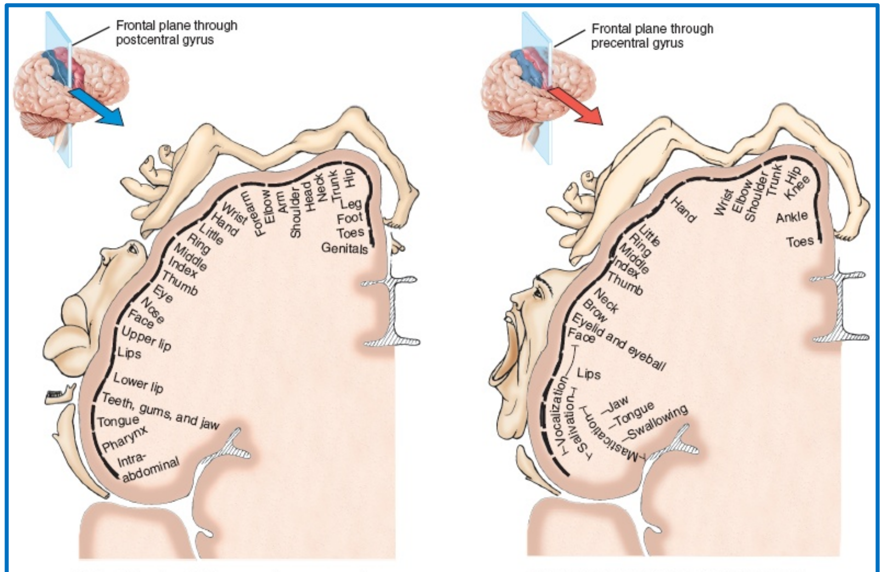
Neurological Injury

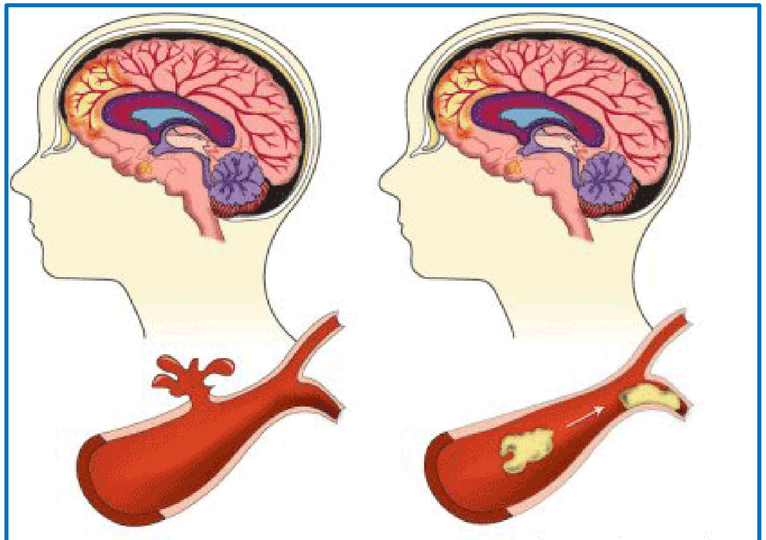
——*Stroke*

- The combination of sensory and motor deficits each person will experience after stroke vary greatly based on the location in the brain.



(a) Frontal section of primary somatosensory area in right cerebral hemisphere

(b) Frontal section of primary motor area in right cerebral hemisphere



A hemorrhagic stroke occurs when a blood vessel bursts within the brain.

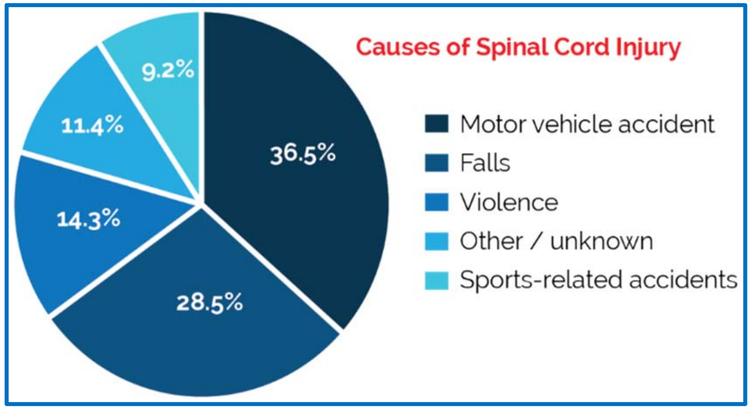
An ischemic stroke occurs when a blood clot blocks the blood flow in an artery within the brain.

Sensory and Motor Cortex

Hemorrhagic Stroke **Ischemic Stroke**

Neurological Injury

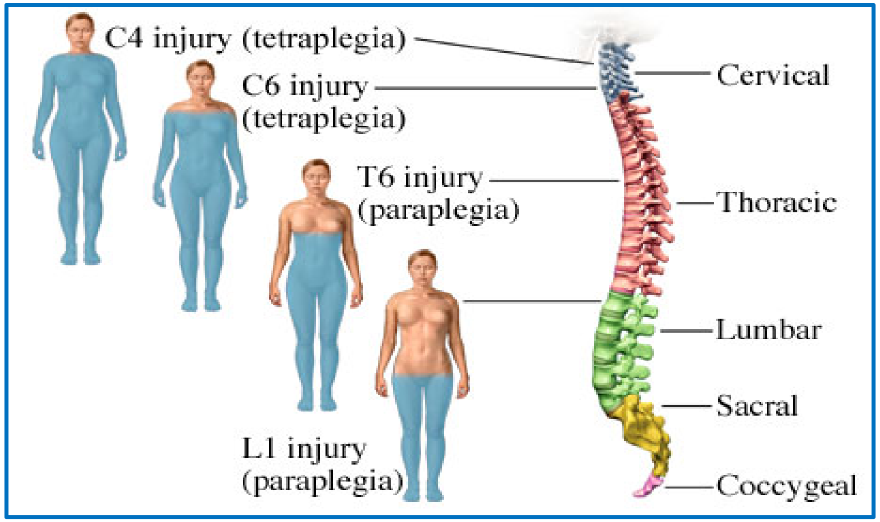
—— *Spinal Cord Injury (SCI)*



* Data from National SCI Statistical Center (NSCISC)

- SCI is a damage to spinal cord that causes loss of muscle function, sensation, or autonomic function in parts of the body served by the spinal cord below the level of the lesion.

- Injuries can occur at any level of the spinal cord and can be classified as complete injury, a total loss of sensation and muscle function, or incomplete, meaning some nervous signals are able to travel past the injured area of the cord.



Paralysis Based on the Location of Injury

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  - State-of-the-art Design
  - Training Mode
  - sEMG Processing and Modeling
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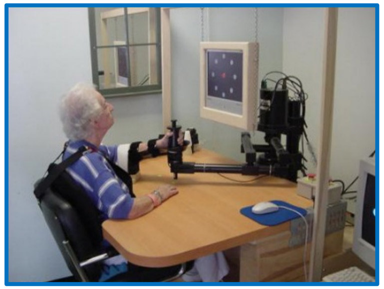
Areas Covered by Rehabilitation Robotics :

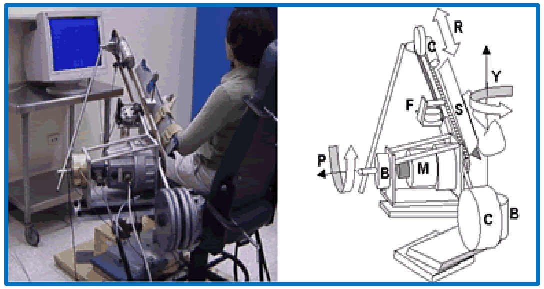
- Rehabilitation and assistive robotics
- Wearable assistive devices
- Behavioral neuroscience
- Biologically-inspired assistive systems
- Human-machine interaction
- Neuro-robotics
- Prosthetic devices
- Locomotion and manipulation assistance
- Technology assessment, ethical and social implications
- …

Upper Limb Rehabilitation Robot

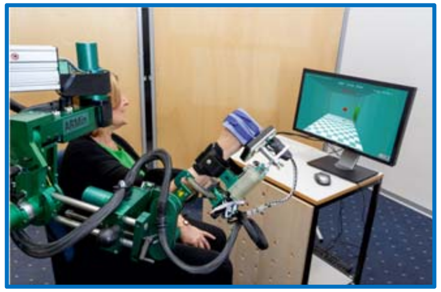


MIT-MANUS,
MIT, 1992

MIME, Stanford,
2000

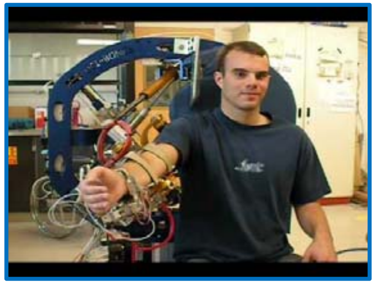


ARM guide, U.C. Irvine,
2000



ARMin, ETH,
2005

1992
2000
2005
2007
2008



BONES,
U.C. Irvine, 2008

Gentle/S,
EU, 2007

CADEN-7, UCLA,
2007

Pneumatic T-WREX,
U.C. Irvine, 2007

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Lower Limb Rehabilitation Robot

Locomat, Swiss,
2004

ReoAmbulator, USA,
2004

MotionMaker, Swiss,
2004

LOPES, University of Twente,
Netherland, 2007

HapticWalker, Germany,
2008

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Robot-aided Training Mode

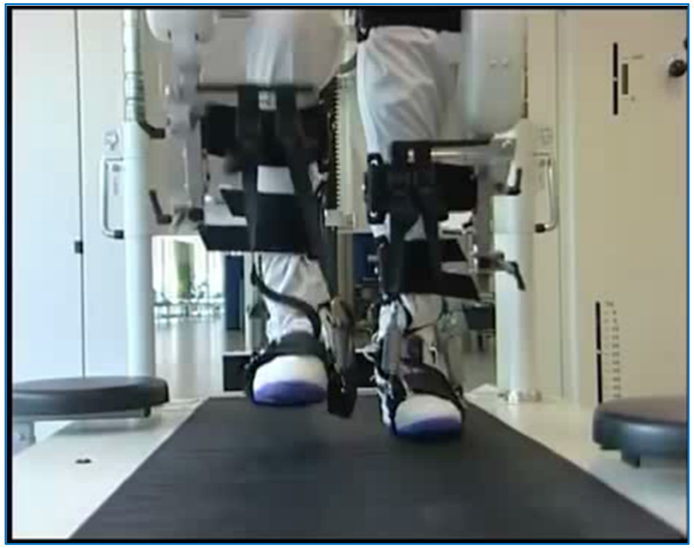
—How the rehabilitation robot interacts with participants during training?

- **Passive Training** —robots provide assistance to move, and patients' active efforts are not considered explicitly in movement control
- **Active Training** —robots provide limited assistance or add resistance according to the participant's motion intention
- **Assist-as-Needed Training** —robots provide as much assistance/resistance as necessary adaptively based on the participant's performance

Mode 1: Passive Training

Positive effects:

- Helps move the affected limb in a manner that self-generated effort cannot achieve.
- Suitable for acute/sub-acute period post-stroke and complete SCI patients who have very weak muscle force.
- Stretching helps prevent stiffing of soft tissue and reduce spasticity.
- Helps increase Range of Motion (ROM).
- …



Example: Gait Training Using Locomat

On the other hand, passive training mode lacks human active engagement and enough sensorimotor stimulation, and therefore is less effective for motor recovery.

Mode 2: Active Training

Active Training

- To provide assistance/resistance according to the participant’ s voluntary motion or motion intention.
- To promote motor relearning through the participant adjusting actively according to force, visual stimulations and feedbacks.
- There are still no general approaches for reliably extracting motion intention and providing assistance in a optimal manner.

Training using ARMin

Too little assistance causes frustration and decreases motivation, whereas too much assistance decreases active output and encourages slacking.

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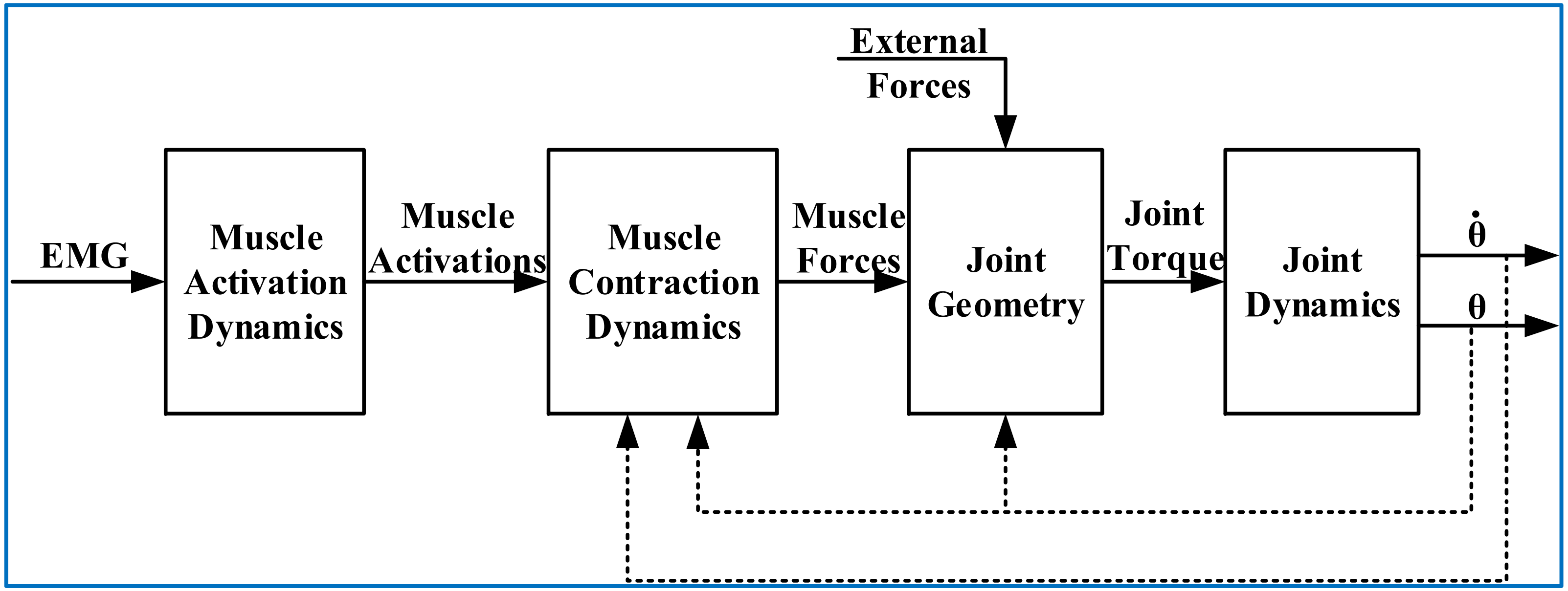
sEMG Processing and Modeling

——*Neuromusculoskeletal Model Method*

- To build a computational model between sEMG and muscle force/torque.
- All subsystem dynamics are subject-dependent, and muscle physiological parameters need to be identified.



sEMG-driven Neuromusculoskeletal Model

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- **Research on Upper-limb Rehab Robot**
  - **Robot Design and Force Feedback**
  - **Training Mode and Control Method**
- Research on Lower-limb Rehab Robot

Upper-limb Rehabilitation Robot

Virtual Training Environment

Visual/Audio Feedback

Haptic Interface

Force Feedback

Robot-aided Training Scenario

CASIA-ARM Rehab Robot

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  - Robot Design and Integrated Modules of sEMG and FES
  - Training Mode and Control Method

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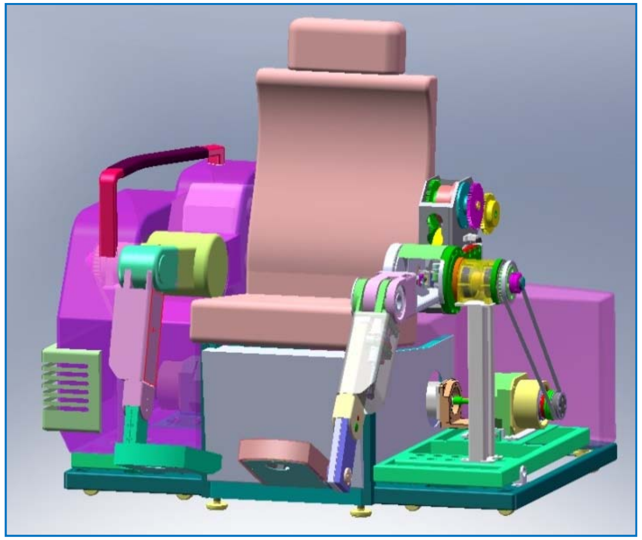
Lower-limb Rehabilitation Robot



Features:

- Three DOFs (thigh, knee, and ankle joints)
- Designed for patients with serious or minor spinal cord injury.
- For patients of height from 1.5m ~1.9m with length adjusting mechanism.

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Lower-limb Rehabilitation Robot

——*Rehabilitation Training Mode*

- By combing the rehabilitation robot and FES, sEMG devices, different training modes can be implemented:

1. **Passive training**: The patient's affected limb is moved by the robot to follow a predefined trajectory.
2. **FES-assisted training**: During the passive training, major muscles are electrically stimulated sequentially based on the motion phases.
3. **Active training**: the robot is controlled to follow the patient's intention estimated by sEMG signals.

Lower-limb Rehab Robot

FES Device

sEMG Sensor

Training Mode

——*FES-Assisted Training*

Video – FES-assisted cycling and pedaling movement

Lower-limb Rehabilitation Robot

——*Rehabilitation Training Mode*

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Lower-limb Rehab Robot

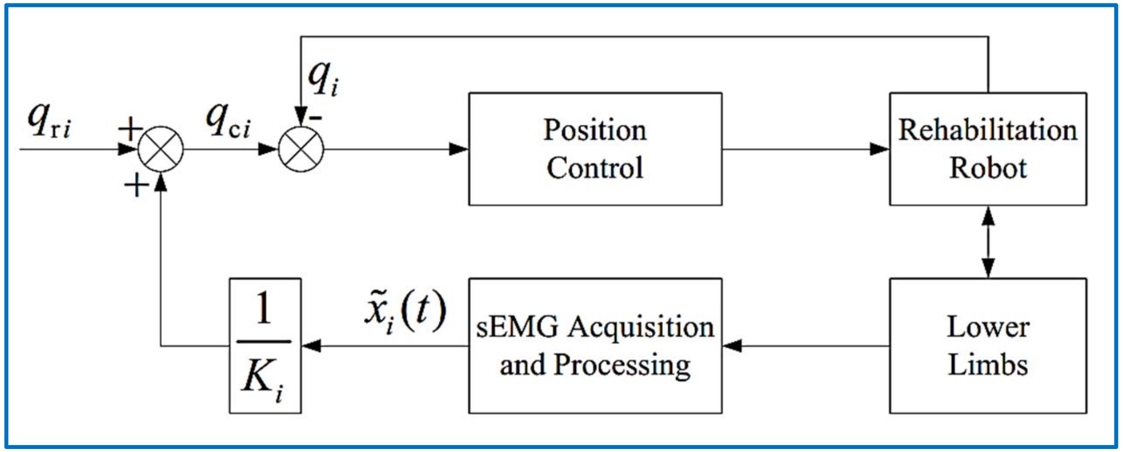
sEMG Sensor

sEMG-Based Active Training Mode

——*Spring-type Impedance Interaction Control*

- The robot’s knee joint angle trajectory is adjusted according to the voluntary contraction of the patient’s two thigh muscles.
- Spring-type training controller:

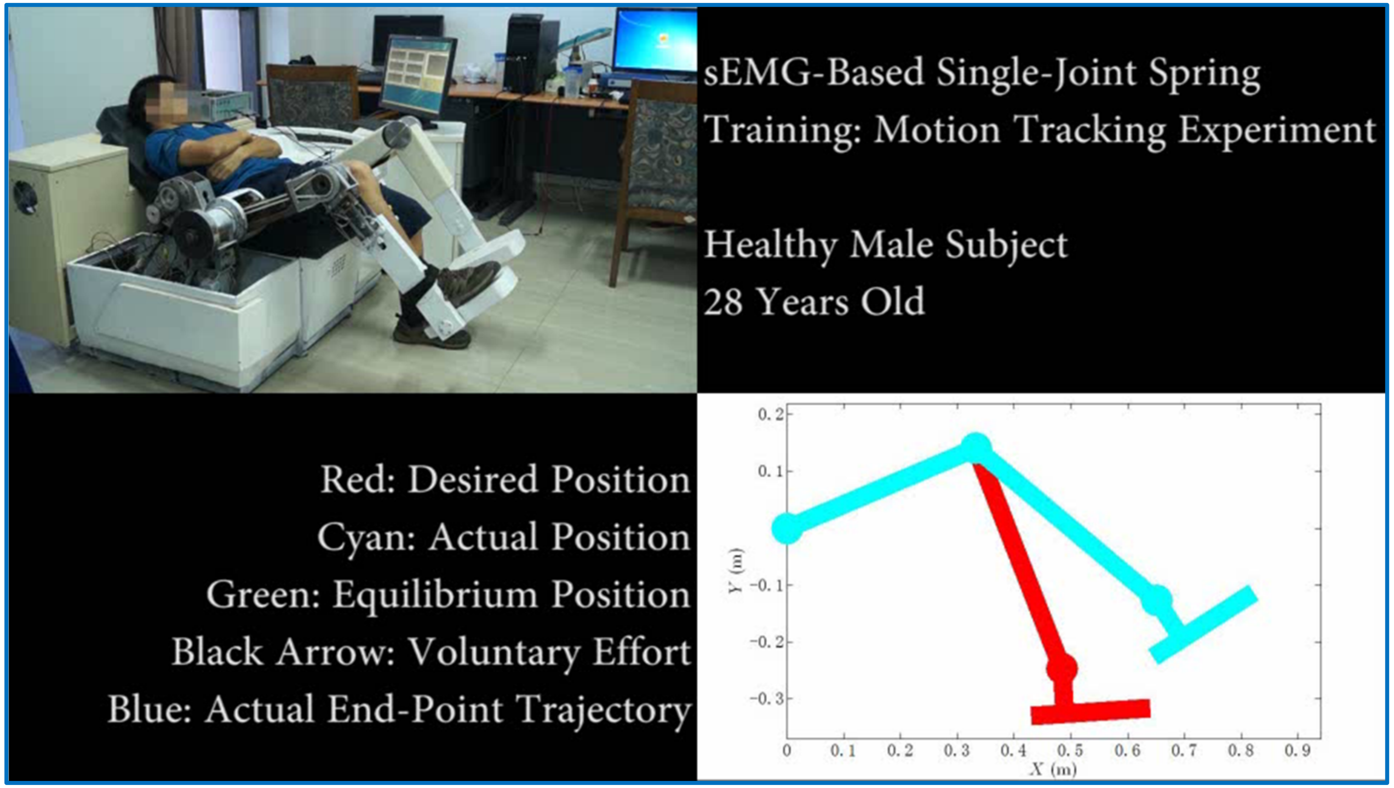
$$\underset{\substack{\uparrow\\\text{sEMG}}}{\tilde{x}_i(t)} = \underset{\substack{\nearrow\\\text{Stiffness}}}{K_i}(\underset{\substack{\nwarrow\\\text{Angle}\\\text{Control}}}{q_{ci}} - \underset{\substack{\nwarrow\\\text{Angle}\\\text{Reference}}}{q_{ri}})$$



Spring-type Active Training Control Loop

Experiment

—Spring-type Active Training Mode



sEMG-Based Single-Joint Spring Training: Motion Tracking Experiment

Healthy Male Subject
28 Years Old

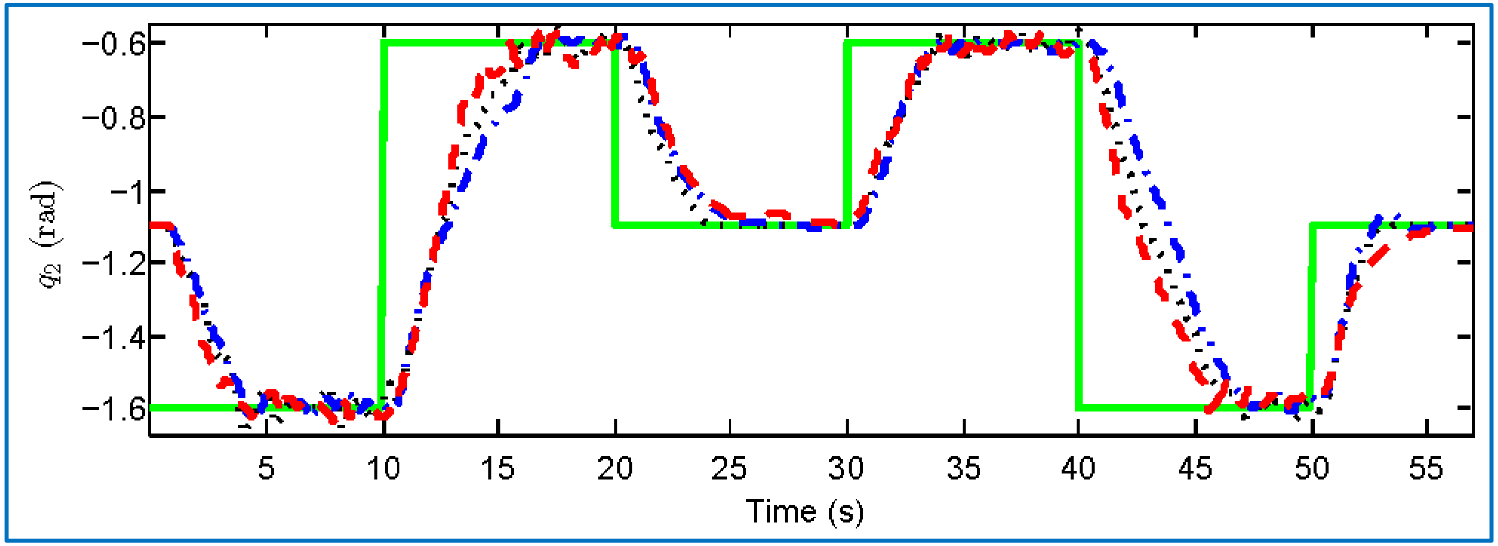
Red: Desired Position
Cyan: Actual Position
Green: Equilibrium Position
Black Arrow: Voluntary Effort
Blue: Actual End-Point Trajectory

Spring-type Active Training Experiment

Experiment Result

——*Spring-type Active Training Mode*

- **Motion Tracking**



- **RMS Error (Last 3 Seconds of Each Step)**

Subject 1	Subject 2	Subject 3
0.0200rad	0.0155rad	0.0237rad

sEMG-Based Active Training Mode

——Damping-type Impedance Interaction Control

- The robot’ s knee joint velocity trajectory is adjusted according to the voluntary contraction of the patient’ s two thigh muscles.
- Damping-type training controller:

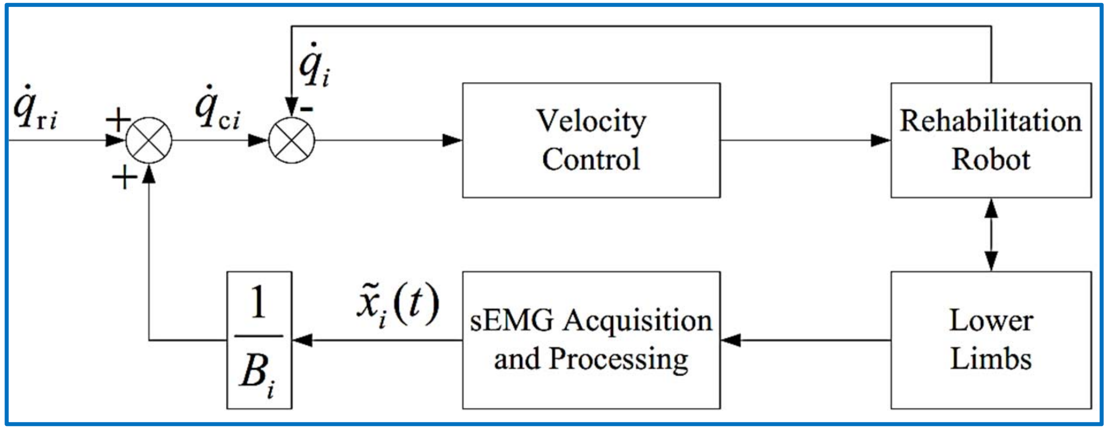
$$\tilde{x}_i(t) = B_i(\dot{q}_{\mathrm{c}i} - \dot{q}_{\mathrm{r}i})$$

sEMG

Damping Factor

Velocity Control

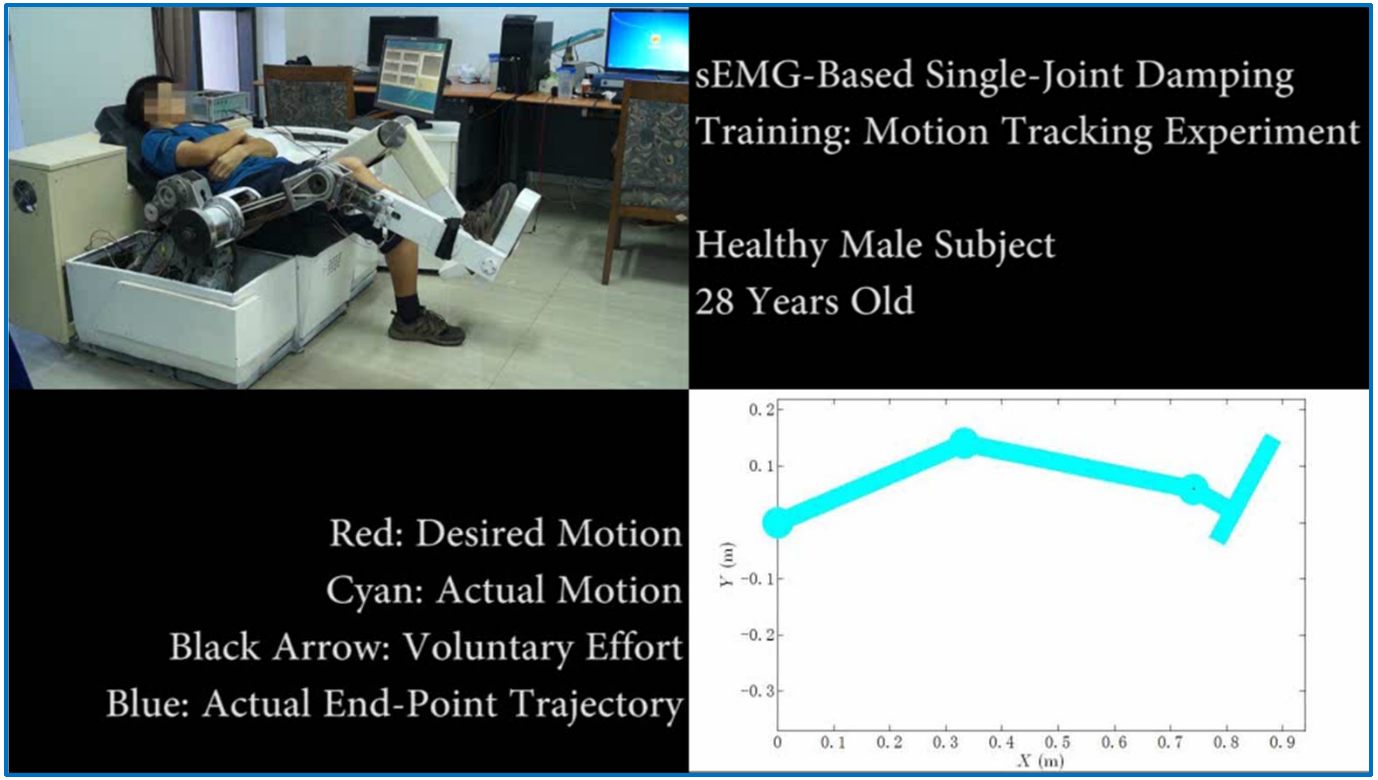
Velocity Reference



Damping-type Active Training Control Loop

Experiment

—*Damping-type Active Training Mode*



sEMG-Based Single-Joint Damping Training: Motion Tracking Experiment

Healthy Male Subject
28 Years Old

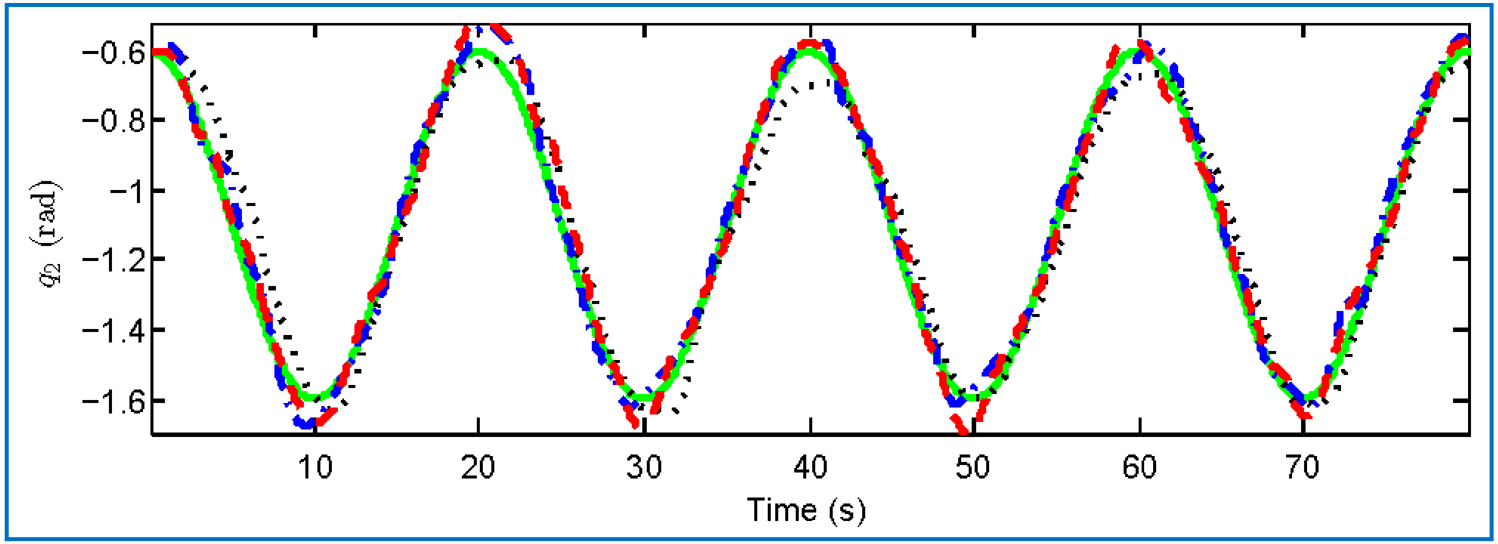
Red: Desired Motion
Cyan: Actual Motion
Black Arrow: Voluntary Effort
Blue: Actual End-Point Trajectory

Damping-type Active Training Experiment

Experiment Result

—— *Damping-type Active Training Mode*

- **Motion Tracking**



- **RMS Tracking Error**

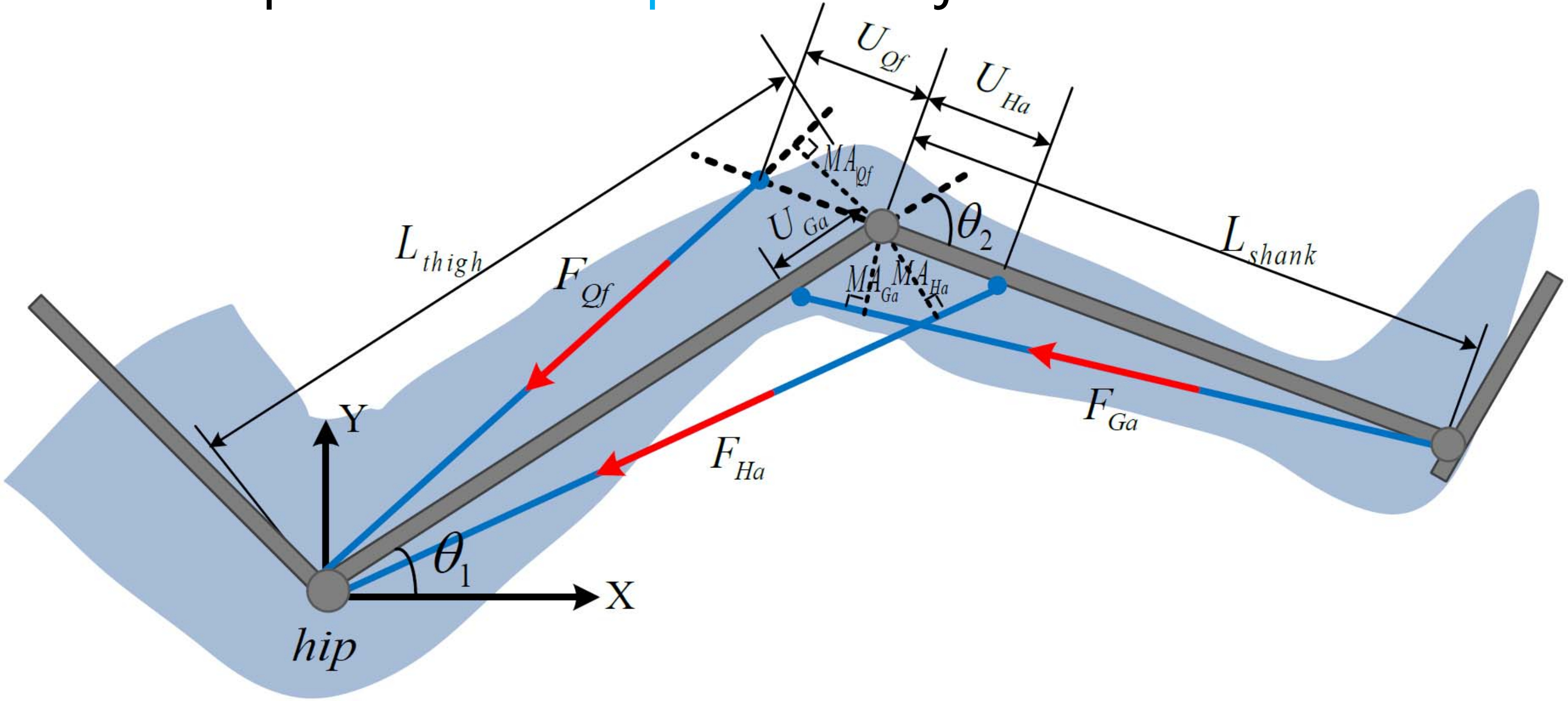
Subject 1	Subject 2	Subject 3
0.0794rad	0.0430rad	0.0483rad

sEMG-Based Active Training Mode

——*sEMG-Driven Musculoskeletal Model*

2) musculoskeletal model

——compute active torque of knee joint



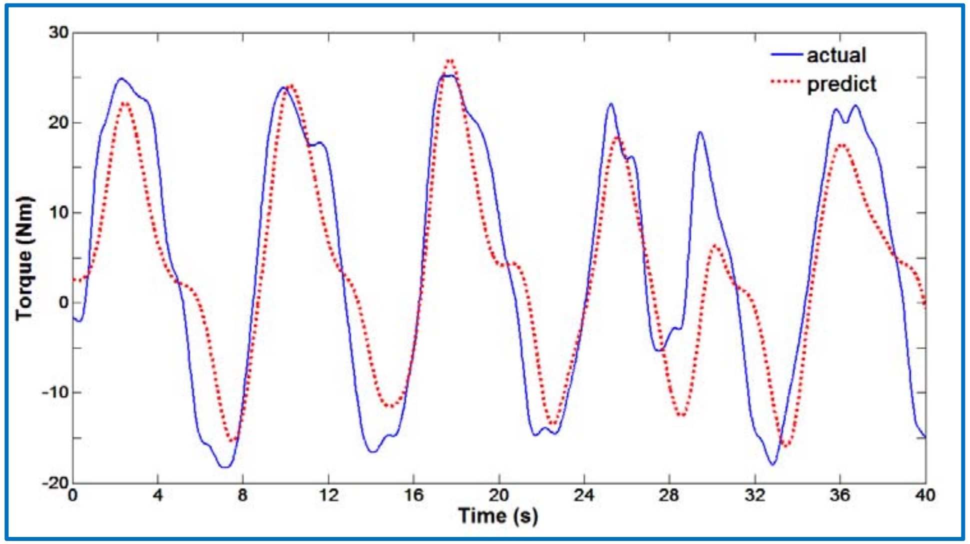
$$T_{act} = \underbrace{K_{Ha}\cdot F_{Ha}\cdot MA_{Ha}}_{\textbf{Ha}\text{mstrings}} + \underbrace{K_{Ga}\cdot F_{Ga}\cdot MA_{Ga}}_{\textbf{Ga}\text{strocnemius}} - \underbrace{K_{Qf}\cdot F_{Qf}\cdot MA_{Qf}}_{\textbf{Q}\text{uadriceps }\textbf{f}\text{emoris}} + \underbrace{\emptyset(\theta_1,\theta_2)}_{\text{correction function}}$$

Musculoskeletal Model Based Active Training

——*sEMG-Driven Musculoskeletal Model*

- **Results of Parameter Identification and Torque Prediction**

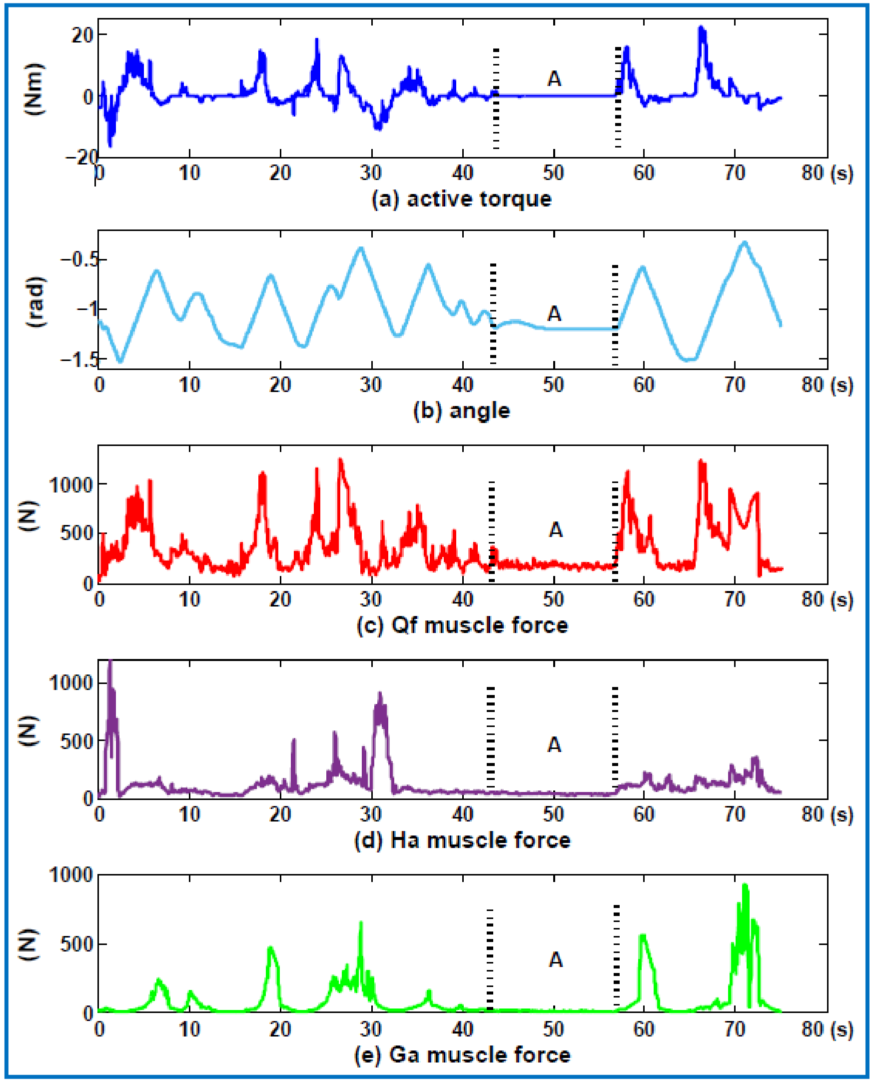
Subject	U_{Qf} **(m)**	U_{Ha} **(m)**	U_{Ga} **(m)**	K_{Qf}	K_{Ha}	K_{Ga}	***RMSE*** **(Nm, Mean ± SD)**
1	0.026	0.024	0.006	0.896	0.737	0.909	5.18 ± 1.54
2	0.028	0.018	0.007	0.830	0.983	0.969	5.64 ± 0.83
3	0.021	0.019	0.008	1.194	0.808	0.956	6.05 ± 0.99



Torque prediction result using the tuned EMG-driven model (RMSE = 7.31 Nm).

Musculoskeletal Model Based Active Training

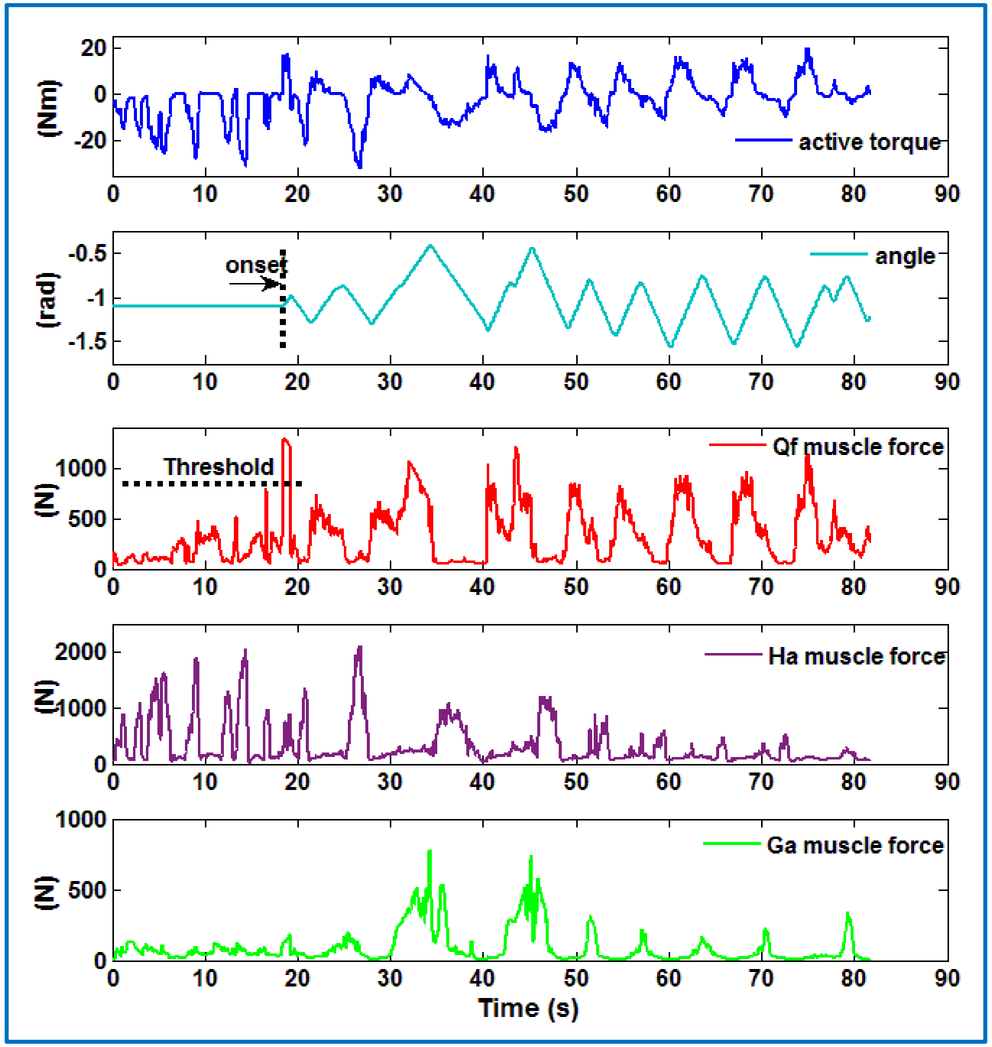
Experiment I: Patient-Driven Voluntary Exercise Training



- The knee joint performs an extension movement when the value of active torque is greater than 0, otherwise performs a flexion movement. When the subject relaxes during the time period labelled as "A", the knee joint remains still.
- Advantages: movement is driven by voluntary effort of the patient's paralyzed limb. Thus, patient's ability could be beneficially exploited to allow a patient to actuate the human-machine system.

Musculoskeletal Model Based Active Training

Experiment II: Muscle-Triggered Voluntary Exercise Training



- The subject's intention to trigger the onset of the robot action is detected by monitoring muscle force. The threshold could be adjusted according to the patient's training needs.
- Advantages: to stimulate specific muscle based on customized requirements. The information, such as trigger time and changes of the selected muscle force, could be useful to make quantitative evaluations.

Musculoskeletal Model Based Active Training

Training Scenario

Demonstration of Robot Motion Control by sEMG

Thank you for your attention!

Since this is an on-going research, more discussions available on site at the tutorial.